The Fate of Fisheries Oceanography

Introduction to the Special Issue

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WHAT IS FISHERIES OCEANOGRAPHY?

Fisheries oceanography can be broadly defined as study of the interaction between marine fish and their environments across multiple life-history stages. Traditional fisheries management approaches estimate population abundance levels as a function of the number of spawning adults without environmental or ecological input, but the field of fisheries oceanography has provided a framework to predict recruitment and define catch limits within an ecosystem context. By seeking to elucidate mechanistic relationships between fish species and their surrounding oceanic habitats, the field of fisheries oceanography aims to provide a solid understanding of fish behavior, population dynamics, and life history with an ecosystem perspective.

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The origin of fisheries oceanography can be attributed to a seminal paper by Johan Hjort titled *Fluctuations in the Great Fisheries of Northern Europe Viewed in the Light of Biological Research*, published a century ago (Hjort, 1914). His research was driven by a desire to understand the effects of migratory behavior and fishing on fluctuations in the abundance of key European fisheries. Hjort discovered that changes in migration had a minimal effect on the number of spawning adults, but that year-class strength was largely driven by the success of first-feeding larvae and eventual recruitment into the spawning stock (Houde, 2008). He termed this idea the "critical period hypothesis" and suggested that survival at the early larval stage was the primary driver of year-class variability (Hjort, 1914, 1926). With over 100 years of research on the topic, Hjort's hypothesis is still a cornerstone of fisheries research and management, although it is now clear that ecological and environmental processes beyond larval survival alone drive strong year classes. The importance of Hjort's early work in defining and steering fisheries oceanography research to this day is reflected by his thousands of citations and in the many papers published this year in a special issue of the *ICES Journal of Marine Science* on "Commemorating 100 years since Hjort's 1914 treatise on fluctuations in the great fisheries of northern Europe" (see Browman, 2014, and references therein). Although the field of fisheries oceanography has matured over the past century, we are still, as Ed Houde put it, "emerging from Hjort's shadow" (Houde, 2008).

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OVERVIEW OF THIS SPECIAL ISSUE

We can ask, 100 years after Hjort's influential paper, where is fisheries oceanography now, and where is it going in the coming century? Although there have been significant technological advances in ocean observations over the past century, a substantial increase in fishing pressure (including the rise of industrial fisheries) and other human uses of the ocean have increased the stresses on marine ecosystems globally. Placed in the context of a changing climate, we are faced with new challenges that will continue to reshape our field for years to come. The articles in this issue offer a sample of how fisheries oceanography research is tackling these challenges, providing an improved understanding of how an ever-changing fluid environment impacts a highly complex ecosystem and proposing strategies for managing these ecosystems sustainably. These articles also highlight that, although the field has progressed over the past century, many of the issues identified by Hjort are still germane today.

Two articles in this issue address some of the same questions posed by Hjort a century ago. **Cury et al.** examine the relationship between spawning fish abundance and number of offspring (the "stock-recruitment relationship") using more than 200 historical time series of marine fish populations worldwide. While their results demonstrate a well-known global pattern of low spawning biomass leading to low recruitment (and often a subsequent asymptote or decrease at high levels of spawning stock), they also point out that parental biomass explains only about 5–15% of recruitment. Although traditional single-species management continues to use spawning stock biomass as the primary indicator for recruitment, these results echo those of Hjort: recruitment estimates must integrate environmental factors and ecological interactions. **Llopiz et al.** revisit Hjort's critical period hypothesis, providing a review of recent research on the early life history of fishes. In addition, the authors discuss the future of larval ecology research, focusing on understanding the impacts of climate change and other anthropogenic stressors.

One of the key advances in fisheries oceanography over the past century has been the establishment of long time-series surveys that have provided the observations needed to test and refine key hypotheses (Hare, 2014). Several such time series operating within the US Large Marine Ecosystems (LMEs) are reviewed by **McClatchie et al.** Among them is the California Cooperative Oceanic and Fisheries Investigations (CalCOFI) program (McClatchie, 2014), which began off the US West Coast in the 1940s, in part to explain the collapse of the vast and economically important California sardine fishery (Steinbeck, 1945; Hewitt 1988; Scheiber, 1990; Bograd et al., 2003). **Sheffield Guy et al.** review the evolution of NOAA's Ecosystems and Fisheries Oceanography Coordinated Investigations (eFOCI) program in the Bering Sea, which has provided great insight into how climate influences fisheries recruitment. Following in Hjort's footsteps, both CalCOFI and eFOCI scientists have taken an ecosystem approach to understanding physical-biological coupling in the ocean, and they continue to pave the way forward for fisheries oceanography. **Zwolinski et al.** demonstrate the utility of fisheries oceanography surveys as platforms for integrating new technologies with old observing standards in support of ecosystem-wide observations. New acoustic technologies can be combined with standard net trawls, the workhorse of fisheries observing since the days of Hjort, to obtain the ecosystem-wide observations needed to effectively manage coastal pelagic species, which are critical to the functioning of the California Current LME.

An emphasis on transitioning from traditional single-species to ecosystem-based fisheries management is driving many of the recent developments in fisheries oceanography. For example, **Peterson et al.** review the development of ocean indicators that are derived from fisheries oceanography surveys and that can be related to the recruitment of a number of commercially important species in the California Current, thus improving our understanding of the environmental linkages of these species as well as their management. Similarly, **Boldt et al.** provide a thorough review of and recommendations for the identification of key indicators that describe and assist with the management of multiple human stressors on marine ecosystems. **Robinson et al.** review interactions among jellyfish, forage fish, and fisheries, and use ecosystem models to compare the impacts of jellyfish blooms in three distinct US LMEs. The global extent of jellyfish, and their potential to increase in abundance in a warming ocean (Richardson et al., 2009; Brotz et al., 2012), speaks to the importance of considering their role in marine food webs.

Among the most significant challenges in the field is to provide the research needed to effectively and sustainably manage our marine resources across multiple time scales. In the short term, this includes the adaptation of fisheries management or conservation protocols in near real time to account for the dynamic and ever-changing marine environment. Although the development and implementation of this concept of "dynamic ocean management" is still in its infancy, **Hobday and Hartog** provide a review of examples from Australia. They demonstrate the utility of incorporating environmental variables that are more direct measures of habitat (e.g., thermal fronts, upwelling zones) into ecosystem models, habitat predictions, and spatial management and harvest strategies, among other applications.

On longer time scales, fisheries management and conservation strategies must be able to adapt to and account for the potential impacts of climate change on the ocean and its living marine resources. In this regard, **Pinsky and Mantua** provide an overview of climate adaptation strategies currently under consideration within the United States and internationally, and offer a "toolbox" of strategies for fostering "climate-ready" fisheries management. Finally, **Kim et al.** review the combined efforts of two leading inter-governmental marine organizations, the International Council for the Exploration of the Sea (ICES) and the North Pacific Marine Science Organization (PICES), to synthesize and promote science-based advice on the impacts of climate change on marine ecosystems in the northern hemisphere. This excellent example points to the need for international efforts to protect our oceans and marine life within a rapidly changing climate.

WHITHER FISHERIES OCEANOGRAPHY?

While progress is clearly being made in fisheries oceanography, there is still much to be done. Technological advances in ocean and fisheries observing are moving the field forward, allowing the collection of ecosystem data at scales relevant to ecological processes affecting survival and recruitment (Houde, 2008). For example, advances in the miniaturization and data collection capacity of electronic "biologging" tags now allow collection of environmental data at the scale of an individual (Bograd et al., 2010; Hazen et al., 2012). New optic and acoustic instruments are greatly improving the observational capacity of ship-based surveys, allowing fine-scale "visualization" of the water column. Fisheries acoustics, in particular, has become a requisite tool for pelagic stock assessment, given its low invasiveness and ability to sample at much finer spatial and temporal scales than traditional techniques (**Zwolinski et al.**). Autonomous observing platforms such as gliders have the capacity to replace many functions of a traditional survey vessel for a fraction of the cost (Ohman et al., 2013; Greene et al., 2014, in this issue), although there are still significant limitations on direct biological sampling (and hence the continued need for shipborne nets). On global scales, a suite of satellite sensors measures surface ocean properties at relatively fine spatial and temporal scales, providing critical data for models of ocean circulation, species distributions, and stock assessments, particularly for remote parts of the ocean that are difficult to sample (Yoder et al., 2010; see Box 1). In addition to the availability of more and higher-quality ocean data, significant progress has been made in constructing ever-improving ocean and ecosystem models. Coupled physical-biological models and end-to-end ecosystem models are allowing fisheries oceanographers to examine the mechanisms of environmental influences on marine ecosystems (Miller, 2007; Fulton, 2010; Curchitser et al., 2013; Franks et al., 2013; Haidvogel et al., 2013; Ruzicka et al., 2013), as well as to evaluate management strategy scenarios (Levin et al., 2009).

With an increase in the quantity and quality of ecosystem-relevant data, new strategies are being developed to integrate these data streams into fisheries management. This move toward

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Box 1. Dedication to Dave Foley

The fisheries oceanography community lost a true champion upon the passing of Dave Foley in December 2013. Dave began his career in fisheries oceanography in 1997 as the CoastWatch Coordinator for the NOAA Southwest Fisheries Science Center's (SWFSC's) Honolulu Laboratory, then continued his CoastWatch work at the Environmental Research Division in Pacific Grove, California, after 2003, providing remotely sensed oceanographic data to the worldwide fisheries and oceanography communities. Dave not only provided data and products to researchers, he was also able to distill complex information into simple ideas that could be easily communicated to others. In addition to his main duties of serving oceanographic data, Dave was a pioneer in applying satellite data to research on understanding spatial patterns in marine species distributions and biodiversity. Dave worked hard to provide fisheries-relevant derived satellite products (e.g., frontal structure, mesoscale activity) and to write code in multiple programming languages to perform the difficult task of combining Lagrangian tracking data with remotely sensed oceanographic data. This program, called Xtractomatic, took advantage of a vast array of data services housed at the NOAA SWFSC Environmental Research Division, and was able to sample each point of a track with variable confidence intervals and for multiple remotely sensed data sets. Other tools have since arisen with similar functionality, but the multitude of papers using Xtractomatic highlights how important a development it was to the field of fisheries oceanography. Dave also realized early the importance of mentoring and teaching to provide continuity in the field, and through his tireless efforts provided support and training to many future fisheries oceanography disciples. Through his advances in providing remotely sensed data as well as awareness to the field, Dave's memory will live on as a key participant in and important contributor to the field of fisheries oceanography.

Box 2. The NOAA Fisheries and the Environment (FATE) Program

Fisheries and the Environment (FATE) is the US National Oceanic and Atmospheric Administration's (NOAA's) premier fisheries oceanography program (http://www.st.nmfs.noaa.gov/fate/index). Begun in 2002 and active nationally, FATE is designed to support NOAA's mission to "ensure the sustainable use of US fishery resources under a changing climate." FATE activities facilitate the development of cross-cutting projects within NOAA and between NOAA and academic partners by conducting and supporting research on ecological and oceanographic change at the population and ecosystem level and from local to ocean basin scales. Over the past decade, FATE has supported close to 150 individual research projects, which have led to nearly 200 peer-reviewed publications, and has conducted annual scientific symposia. Programmatically, FATE focuses on the development, evaluation, and distribution of leading ecological indicators, maintenance and examination of time series for climate trends, and incorporation of environmental information into models used for fisheries and ecosystem management. FATE aims both to advance the field of fisheries oceanography and to provide a framework for ecosystem-based fisheries management.

ecosystem-based fisheries management has been a long-standing goal in the field, although its implementation has been slow (see summary in Link et al., 2002). Ecosystem indicators offer tools for summarizing ecosystem status independent of management objectives (**Boldt et al.**; **Peterson et al.**; see Box 2), including synthesizing physical forcing (e.g., sea surface temperature), species-specific properties (e.g., mean weight/length ratio), ecosystem characteristics (e.g., total biomass, species richness), and human dimensions (e.g., fisheries revenue). These indicators provide information on status, trends, and the ability to differentiate between natural variability and anthropogenically induced climate change, particularly when data are available as a long time series (e.g., > 30 years) and at multiple locations within an ecosystem (Levin et al., 2009).

Enhanced observing and modeling capacity is also providing new opportunities for improving fisheries management at both short (e.g., weekly) and long (e.g., climatic) time scales. Dynamic ocean management, in which management protocols are adapted in response to changing ocean conditions, offers a promising opportunity to improve the efficiency and sustainability of target fisheries while minimizing nontarget bycatch (Howell et al., 2008; Hobday et al., 2014; **Hobday and Hartog**; Lewison et al., in press). At much longer time scales, climate adaptation strategies are required to prepare for potentially substantial global changes in marine ecosystems (Pörtner and Peck, 2010; Poloczanska et al., 2013; **Pinsky and Mantua**), including species range shifts (Perry et al., 2005; Nye et al., 2009; Pinsky et al., 2013), biogeochemical changes (e.g., increasing ocean acidification and hypoxia; Feely et al., 2009; Doney et al., 2012), phenological shifts (Edwards and Richardson, 2004; Durant et al., 2007; Sydeman and Bograd, 2009; Ji et al., 2010), and changes in productivity and community structure (Brander et al., 2007; Cheung et al., 2009; Barange et al., 2014).

In summary, while there have been great advances in the 100 years since Hjort's seminal work, it would appear that the next century will be an exciting time for the field of fisheries oceanography.

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